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CRREL REPORT 89-7

US Army Corps of Engineers
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Water detection in the coastal plains of the Arctic National Wildlife Refuge using helicopter-borne short pulse radar

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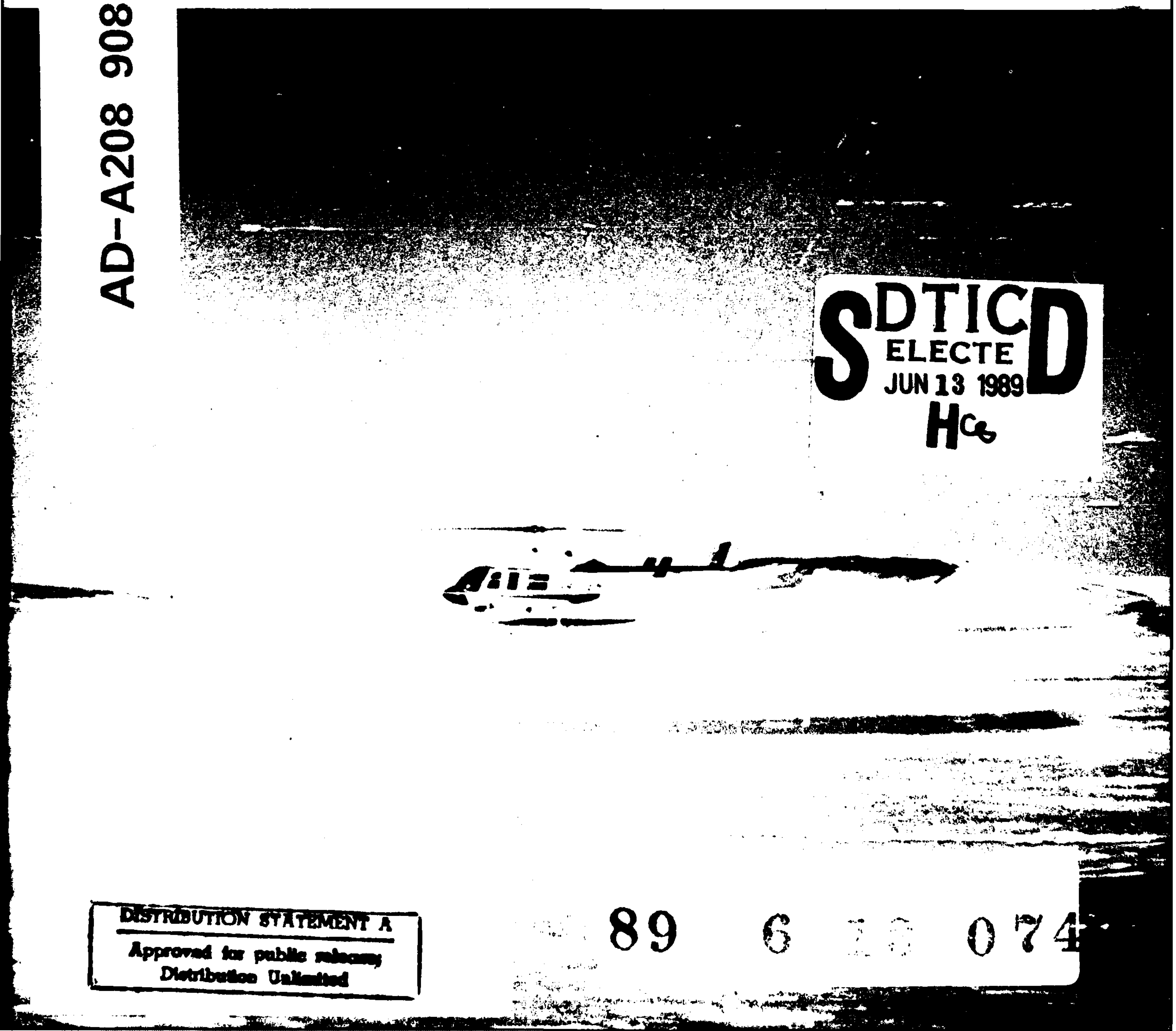

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Ice mound on the Sadlerochit River in the Arctic National Wildlife Refuge. (Photo by D.J. Calkins.)

CRREL Report 89-7

April 1989

Water detection in the coastal plains of the Arctic National Wildlife Refuge using helicopter-borne short pulse radar

Steven A. Arcone, Allan J. Delaney and Darryl J. Calkins

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A helicopter-borne short-pulse radar survey of water resources was performed along the coastal plains of the Arctic National Wildlife Refuge in March 1988 to help evaluate the potential environmental impact of resource exploration. The surveys concentrated on the major rivers and a few lakes of the area and were performed at approximately 5-m altitude and 5-m/s flight speed. The radar antenna was externally mounted on the helicopter skids and emitted 6- to 7-ns pulses whose bandwidth was centered near 500 MHz. The locations of most surveys were determined by a satellite positioning system. The ice cover was generally frozen to the river bed in all areas investigated, except for open water reaches within extensive icings that developed downstream from hot springs. The radar data revealed sub-ice water channels within the icings as well as water beneath ice mound features in icing areas in the delta regions of the major rivers. A systematic radar survey, augmented with drilling, of one chain of three mounds allowed the water volume to be estimated, but did not reveal any external source. It is speculated that a more intensive ground-based radar and drilling survey would clearly identify whether the water source was confined to the talik or was from an aquifer system.

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PREFACE

This report was prepared by Dr. Steven A. Arcone, Geophysicist, and Allan J. Delaney, Physical Science Technician, Snow and Ice Branch, and Darryl J. Calkins, Chief, Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research project was provided by the U.S. Department of Interior, Fish and Wildlife Service, Anchorage, Alaska, Agreement 14-16-0007-08-7719 and by DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground*, Task SS, Work Unit 014, *Electromagnetic and Radiative Characteristics of Snow, Ice and Frozen Ground*, and Work Unit 025, *Water Supply Quantification on Winter Battlefields*.

The authors thank Dr. George Ashton and Dr. Lindamae Peck of CRREL for technically reviewing the manuscript of this report. They gratefully acknowledge the assistance given by George Elliot, of the U.S. Fish and Wildlife Service, who was the flight navigator and selected the transect locations. They also thank their pilot, Dean Priddy of ERA Helicopters, for his skillful and safe flying.

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STEVEN A. ARCONE, ALLAN J. DELANEY AND DARRYL J. CALKINS

INTRODUCTION

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) was contracted by the U.S. Department of Interior, Fish and Wildlife Service (FWS), to conduct geophysical water availability studies in the Arctic National Wildlife Refuge (Arctic NWR) at the end of the 1988 winter season. This information was necessary to determine the environmental impact of possible development of the area's natural resources. The area is frequently referred to as the 1002 area of the Arctic NWR as described in Section 1002(c) of the Alaska National Interest Lands Conservation Act of December 1980.

This report provides the data that were collected during the field work, a description of the equipment and a brief analysis of the techniques used in the study. Typical radar returns obtained during the survey will be discussed to indicate the type of information that may be abstracted from the data, all of which are given in a supplementary data report (CRREL Internal Report 1028).

OBJECTIVE

The objective was to identify the presence of unfrozen water beneath selected rivers and lakes on the coastal plain, Arctic NWR, using both a high frequency short pulse radar mounted externally to a helicopter and a hand-held magnetic induction conductivity meter. Occasional ground truth data of ice thickness and water depths were collected to verify the remotely sensed data.

STUDY AREA

The study sites were confined to the major streams and lakes on the coastal plain of the Arctic NWR. The major streams identified by FWS personnel for sampling were the Canning, Tamayariak, Katakturuk, Sadlerochit, Hulahula, Okpilak, Jago and Okerokovik Rivers and Itkilyariak Creek. Lakes were chosen on the basis of our ability to identify their location on the 1955 topographic maps from visual observation. Figure 1 is a general location map of the area.

The study took place on the Arctic Coastal Plain in Northeast Alaska, with Kaktovik on Barter Island being the major civilian community in the area. We were based at the Barter Island U.S. Air Force Distant Early Warning Radar Station (DEW line). Detailed geographic and climatic summaries of the area can be found in the *Arctic National Wildlife Refuge: Alaska, Coastal Plain Resource Assessment* (US DOI 1987).

Hydrologic and hydraulic information on the streams and lakes is very limited and confined to only spot measurements when available at all. Summer information concerning water flow and quality is available for some streams. Winter documentation, if any exists, on the hydrology, hydraulics or ice conditions of the rivers in the Arctic NWR could not be located at the time of report preparation.

INSTRUMENTATION

Two distinctly different types of electromagnetic equipment were tested. One was a short pulse

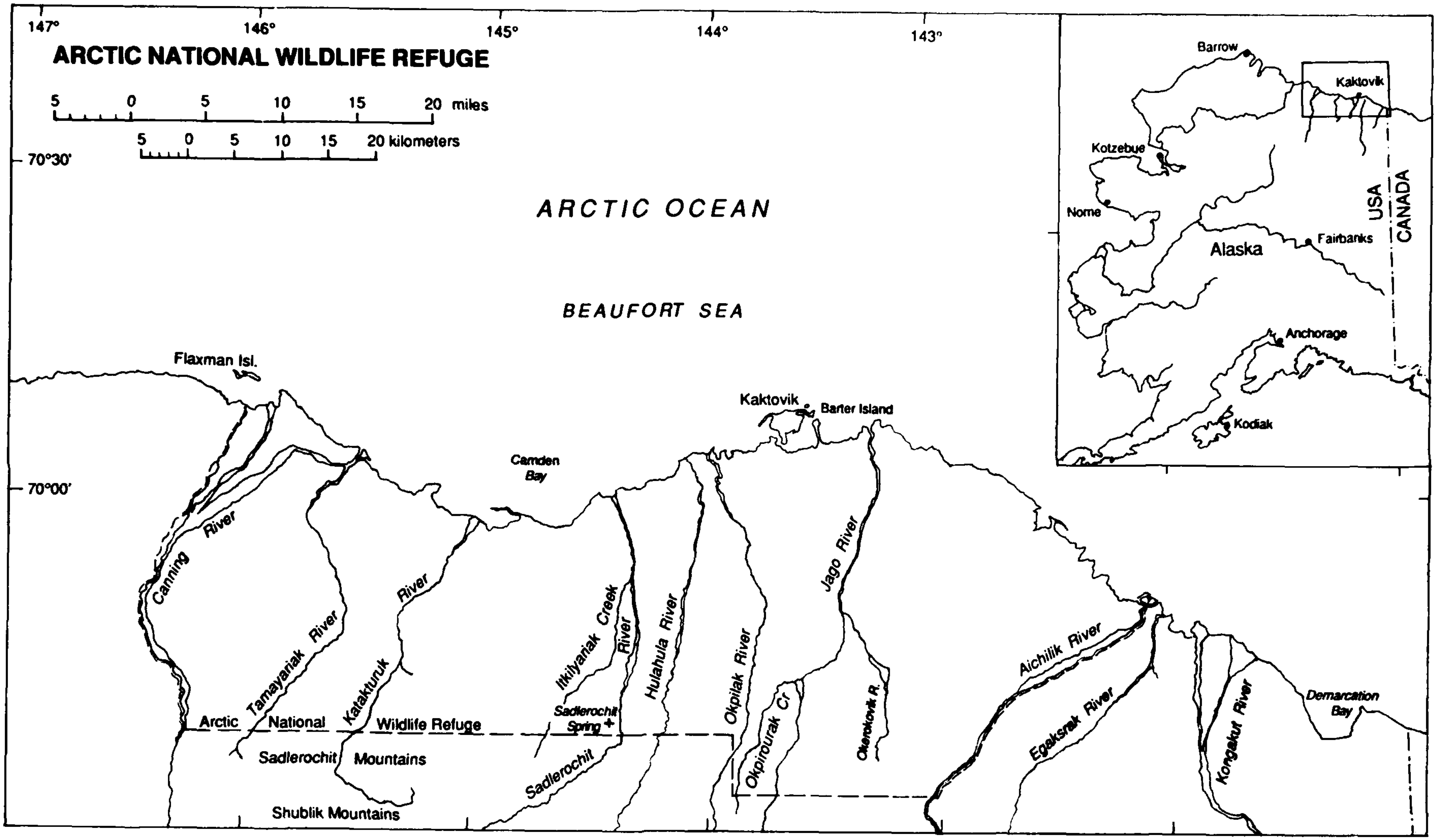

Figure 1. General location map of the study area in the Arctic NWR.

radar system operating near 500 MHz while the second was a magnetic induction conductivity instrument that operates at 39 kHz. The radar technique was used to profile interfaces between materials with different dielectric constants; the conductivity method measures bulk conductivity of the ground in the vicinity of the instrument. Both systems had been used in previous river ice studies to locate unfrozen water beneath ice sheets (Arcone and Delaney 1987, Arcone et al. 1987).

Short pulse radar

Short pulse radar is also known as impulse radar or ground-penetrating radar. The fundamental concept in short pulse radar is to couple some sort of discharge device to a very broadband antenna to radiate a short pulse and receive a reflection whose time of propagation can be measured with suitable clocks in a control unit. The antennas are usually resistively loaded dipoles, the design of which seeks to attenuate the oscillations of the current discharge. Such broadband antennas sacrifice the advantages of conventional radar antennas—high gain, narrow beamwidths, efficiency—to permit this short pulse shape, an example of which is shown in Figure 2. Range resolution is always at a premium; angular location is presumed directly beneath the antenna, for want of any directionality in the beam radiation pattern. Frequency spectra of the pulses in commercial models are centered between 50 and 1000 MHz with usually a 100% bandwidth. Our unit is centered near 500 MHz, reasons for which are discussed at the end of this section. An airborne antenna radiates a single broad lobe with minimal pulse width. The major drawback of airborne antennas is the interference of radiation reflected from the aircraft, examples of which will be shown later. Background removal programs were not yet available for this radar system.

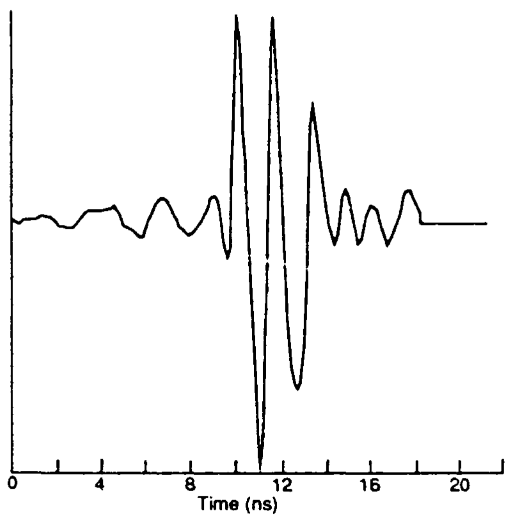

Figure 2. Pulse shape of transmitted signal.

The transmitter and most of the receiver electronics are placed at the antenna terminals to reduce noise, and both antennas and electronics are often placed in one package (Fig. 3) that is shielded to reduce back radiation. The received signals are immediately amplified and then sampled to convert the frequency content into the audio range for tape recording and data display on conventional

Figure 3. Transmitter and receiver antenna housing assembly mounted externally to a Bell 206L Jet Ranger.

graphic devices. The sampled returns are reconstructed into scans extending over time windows ranging generally from about 50 to 2000 ns.

A control unit sets the scan rate (8/s), time windows, overall gain and the all-important TRG (time range gain) function. This function allows the gain to be varied over the scan to enable suppression of the strong early returns and amplification of the weaker later returns. A small oscilloscope is used for viewing the scans and data are recorded on a cassette tape recorder. A variety of high- and low-pass filter settings are available to exclude most ambient noise. The system is powered by batteries.

The necessary time range window is determined by the expected time of return for the deepest reflection (or "event") sought. The free-space velocity c of electromagnetic waves is 30 cm/ns, so that every meter of altitude adds 6.2 ns to the needed time window. Propagation velocities in earth materials are much slower, varying from about 17 cm/ns in dry soil or ice to about 3 cm/ns in icy water. Pulse distortion and absorption will result when wave velocity in a material strongly depends on the frequency of the radiation because pulses contain a broad spectrum of frequencies. This is not a concern for propagation in ice, but is for water. Only depths to the water surface could be measured; water depths could not be measured because of the extremely high absorption (~24 dB/m) and pulse distortion that occurs in 0°C water at this high frequency.

A basic rule of radar surveying is to go as slowly as possible as this will afford the best quality in the data; in the air 2 m/s is ideal. Data have been successfully recorded at speeds between 2 and 9 m/s at 8 scans/second. Higher scan rates are necessary at greater speeds. Table 1 shows the approximate ground area of sensitivity for one scan as a function of altitude for the GSSI model 3102 antenna (center frequency ~ 500 MHz) operating at 8 scans/s at speeds up to 8 m/s. The calculations are based on a measured transmit-receive 3-dB beamwidth of 70° (Arcone et al. 1986) in both principal radiation planes. Snell's law can be used to compute the area of sensitivity at the bottom of an ice sheet (Arcone et al. 1986). The resulting values are slightly lower than those of Table 1 (considering altitude to equal height above subsurface water) due to refractive focusing of the radiowaves when propagating from air into ice.

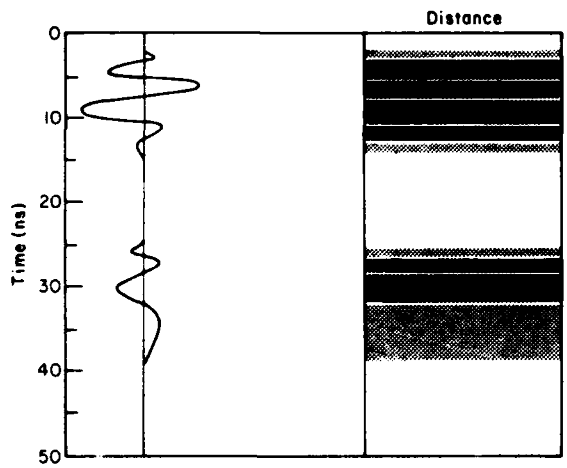

Figure 4. Idealized radar returns and equivalent graphic display, should these returns remain unchanged over a short distance.

Table 1. Approximate ground area of sensitivity as a function of altitude based on the 3-dB beamwidth of the pulse center frequency. Values are good to ±10% for scan rates between 8 and 50 s^{-1} and flight speeds up to 8 m/s.

Altitude (m)	*Area (m^2)*
3.0	16
4.5	35
6.0	60
7.5	90
9.0	130

The most common method of data display is grey-scale intensity modulation on electrosensitive paper, an idealization of which is shown in Figure 4. Darkness is proportional to signal amplitude and the horizontal bands represent the consecutive positive and negative oscillations of the pulse waveform. The chart paper rolls out as fast as the data are recorded on magnetic tape, which means that it takes as long to display data as it does to do a survey. The advantage of this display is that the banding formed by the density of the consecutive scans allows the eye to follow easily the continuity of various events within a profile. The disadvantage is that individual waveforms cannot be readily examined as in a seismic section, but must be retrieved, which is not easy unless they have been digitally recorded and stored, as one manufacturer now offers.

The depth D of a reflection is determined from the time delay t_d between two events (two series of bands) such that

$$D = \frac{ct_d}{2n}$$

where n is the index of refraction of the material (1.79 for ice). The factor of 2 accounts for the round-trip of the echo. In the surveys discussed here, the first event (e.g. Fig. 5) is the ice surface reflection and the second event is usually the reflection from the ice/water or ice/riverbed interface. An ice/water reflection is generally of far greater amplitude than either an air/ice or ice/riverbed interface reflection and is therefore easy to recognize. Theoretically the ice/water reflection is more than 7 dB stronger than an ice/air or ice/gravel interface reflection. In practice, for a snow-covered surface, the ice/water reflections were 20–32 dB greater than the air/ice-snow reflections. This was most likely due to the impedance matching of the air to the ice by the intervening snow layer. Such a layer must have a density of about 0.4 kg/m^3 (n = 1.3) and a thickness of about 15 cm, values that are entirely plausible for this area in late March, to severely depress the dominant frequencies of our radar. Bare ice surfaces gave much stronger reflections.

The choice of a 500-MHz antenna unit was based on our previous experience (Arcone and Delaney 1987) with this unit and on other scientific considerations for this particular task. The 500-MHz unit is small, lightweight and easily mounted on struts. It radiates sufficient power to have allowed airborne penetration of 28 m of ice in an alpine glacier, and provides sufficient resolution to measure thicknesses as small as 30 (±3) cm. Additionally, the unit is shielded to minimize clutter (unwanted reflections) from the aircraft. Lower frequency units are far heavier, poorly shielded, give less resolution and probably would not have provided any additional information, such as water depth, despite the increased power of lower frequency units, and the increased penetration ability of lower frequencies. The reason for this is the high contrast in index of refraction between air and water (considering the ice between). This contrast makes reflections from any bottom slope greater than 6° relative to the ice surface almost impossible to detect. This is because either the returning energy is beyond the angle of critical refraction (i.e. the transmitted energy propagates parallel to the surface) or because the returning energy is refracted beyond the antenna's beam width.

Magnetic induction

Magnetic induction is a ground-based technique for measuring ground conductivity that we implemented in one very limited test during this study using an EM-31, an instrument designed and marketed by the Geonics Co. of Mississauga, Ontario. (See Arcone et al. [1987] for further details of operation on ice-covered rivers.) The instrument is lightweight, consisting of a 3.66-m-long boom with an antenna on each end with a readout device in the center of the boom. The instrument is sensitive to about 7-m depth and was used to search for any subsurface water leading to or present under three ice mounds that were clustered on the Sadlerochit River. Readings were consistently less than 0.1 mS/m (millisiemens/m) everywhere but over the mounds, where readings rose to about 1.4 mS/m, which indicated the presence of water.

After about 1 hour the low temperatures (< −30°C) began to affect battery strength. Therefore the instrument was not used again because of the time it took for obtaining such a limited amount of data.

Water conductivity

This quantity was measured in a few places with a d.c. conductivity meter (Yellow Springs Instrument model 33). The sampling head had to be continuously held in the water to prevent ice from forming within it. This information is needed to evaluate the potential for the radar to penetrate the water depth. The values were 70 μS/cm on the Tamayariak (line GL3) and 26 μS/cm on the Sadlerochit (line IL2), the latter value of which indicates very fresh water and the possibility of a few feet of penetration using our radar. However, none of our data indicated any significant water bottom returns.

Ice augers

A motorized ice auger (a General 21 gas-powered unit) was brought for expediting drilling through the thick ice sheet, but this unit failed in the low temperatures because of loss of resiliency in the diaphragm of the carburetor. Consequently all augering was done by hand. Ice and water depth were measured with a CRREL ice depth gauge, which is a wired tape with a retractable bar at the end.

GPS

The global positioning system (GPS), a Motorola Mini-Ranger with a Motorola Eagle receiver, was battery operated inside the aircraft cabin. The GPS antenna was attached to the top of the radar antenna (Fig. 3) as part of the aircraft external load installation. Mounting directly to the aircraft fuselage would have required additional FAA approval.

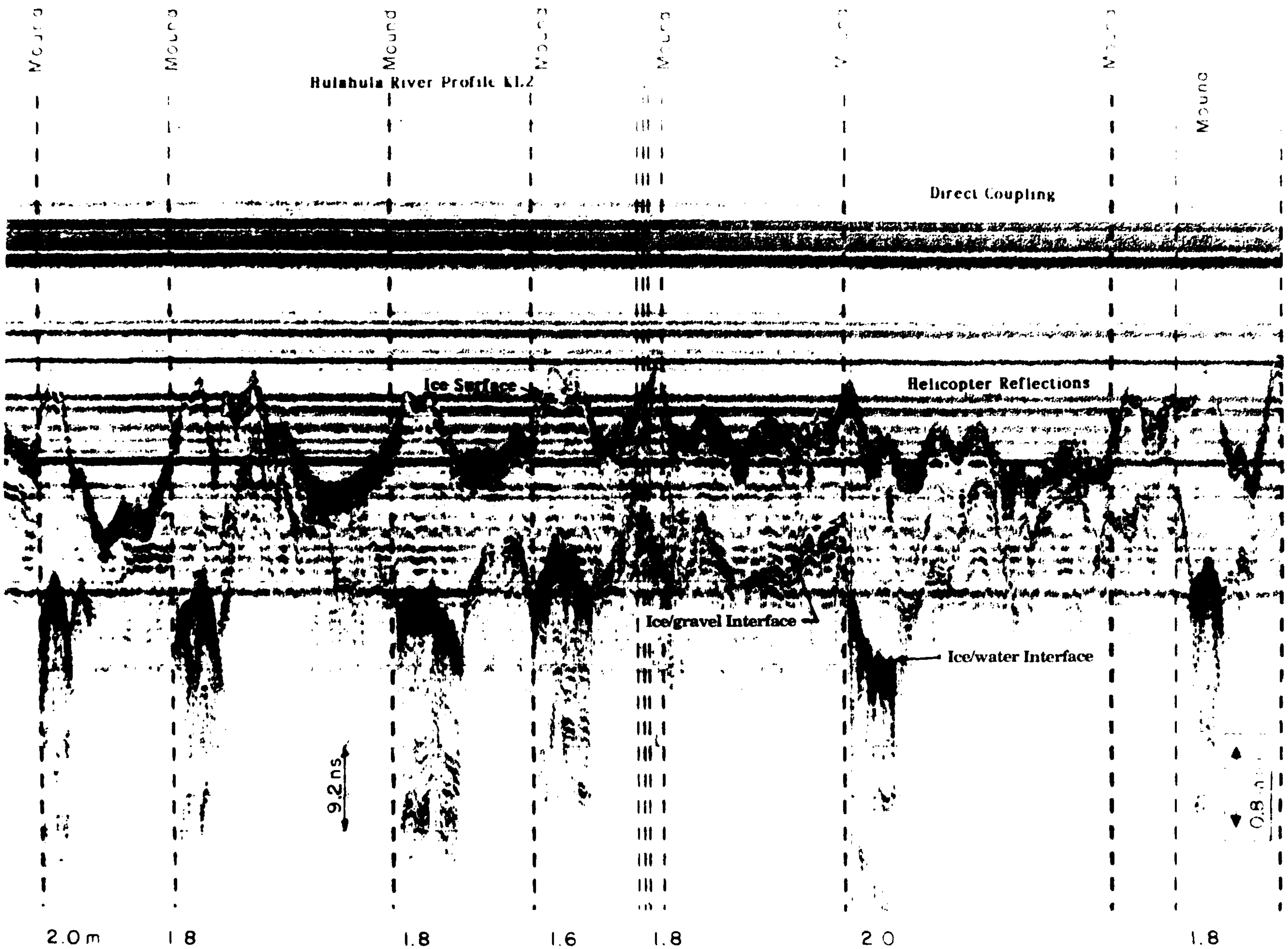

Figure 5. Radar returns over the Hulahula River, profile KL2.

Best operation seemed to occur when the GPS antenna had an unobstructed view to the satellites whose angular elevation above the horizon was always 13–50°. GPS data were read from a Toshiba 1100 lap-top computer. Satellite availability during daylight was generally between 0700 and 1100 local time (–9 hours from GMT). The repeatability of the GPS was checked using the Barter Island aircraft hangar as the reference.

Three satellites were required to start the positioning procedure from an entered, estimated coordinate set, and at least two satellites "locked in" were required to maintain system operation.

At any location, the readings would vary within about ±0.3 seconds of latitude or longitude, which was far more accurate than required. Readings to within about 3 seconds could be made in flight. During sharp turning maneuvers by the helicopter, the GPS would often lose its lock with the satellite signals (possibly due to interference between direct and helicopter-reflected transmissions), which sometimes caused it to compute erroneous coordinates. Difficulties then arose in obtaining accurate coordinates when the GPS tried to redetermine position with only two satellites available.

RADAR DATA COLLECTION

Generally, the aircraft maintained a speed of 5 m/s in a relatively horizontal plane with the radar antennas approximately 3–5 m above the ice surface. Local wind and snow conditions over the rivers on occasions required the pilot to fly at both slightly higher air speeds and higher elevations for safety reasons. The capability to fly relatively level also depended upon the terrain features and wind conditions, the latter of which could influence the direction in which a radar profile was obtained. As the radar data were being collected, event markers were also entered on the recording tape to indicate the location of special terrain or ice conditions. Handwritten notes describing these special features assisted in the interpretation.

POSITIONING

Initial identification of ground position was made from the USGS 1:63360 quadrangle sheets. Coordinates were determined from them at least 50% of the time because of the short time window available for the limited number of satellites. When the GPS was available, coordinate positions were taken at the beginning and end of each transect. The GPS was the preferred method because the 1955 USGS maps in this area do not have the horizontal control precision of the GPS. In addition, stream features identified on the maps such as flow channels, islands, etc., can change from year to year. With the flat terrain, it was difficult to determine position from a USGS map unless a major surface feature could be sighted. Lines for which GPS positions could be obtained are given in Appendix A.

Some transects were flown with no definite control on the end positions or time of the run. These uncontrolled transects were often flown down a meandering channel in a zigzag pattern to detect potential sources of water beneath obvious surface ice features. The location of these transects can be placed only in a general area on the USGS maps.

RESULTS AND DISCUSSION

Airborne radar data (general)

Over 110 cross-sectional and longitudinal surveys were conducted on the rivers mentioned earlier, in addition to survey flights across 16 representative lakes in the region. These locations are identified in CRREL Internal Report 1028. This section will discuss a limited number of examples to show how they may be analyzed for the depth, presence of water, and other factors. The example of Figure 5 is longitudinal profile KL2 on the Hulahula River, which spanned several elongated "ice mounds" (we had no prior knowledge as to which mounds might have water beneath them). The figure is a practical realization of the idealization of Figure 4. Using the typical profile speed of 5 m/s, we judge this record to be about 1200 m long. This distance scale should generally apply to all the radar records, as they have all been displayed at the same chart speed and undergone the same photographic reduction.

There are several radar events in Figure 5 that are labeled. The heavy dark band across the top is the direct coupling between transmit and receive antennas, both of which are contained in the single unit shown in Figure 3. This is followed by several more horizontal bands that are reflections from the helicopter fuselage. The first wavy event is the ice surface reflection. The wavy pattern of this and subsequent reflections is due to gradual fluctuations in helicopter altitude and the sometimes abrupt height of the surface ice features. Beneath this surface reflection is a second reflection that increases dramatically in intensity in seven zones. These zones are reflections from subsurface water. Where the intensity of the subsurface reflection is

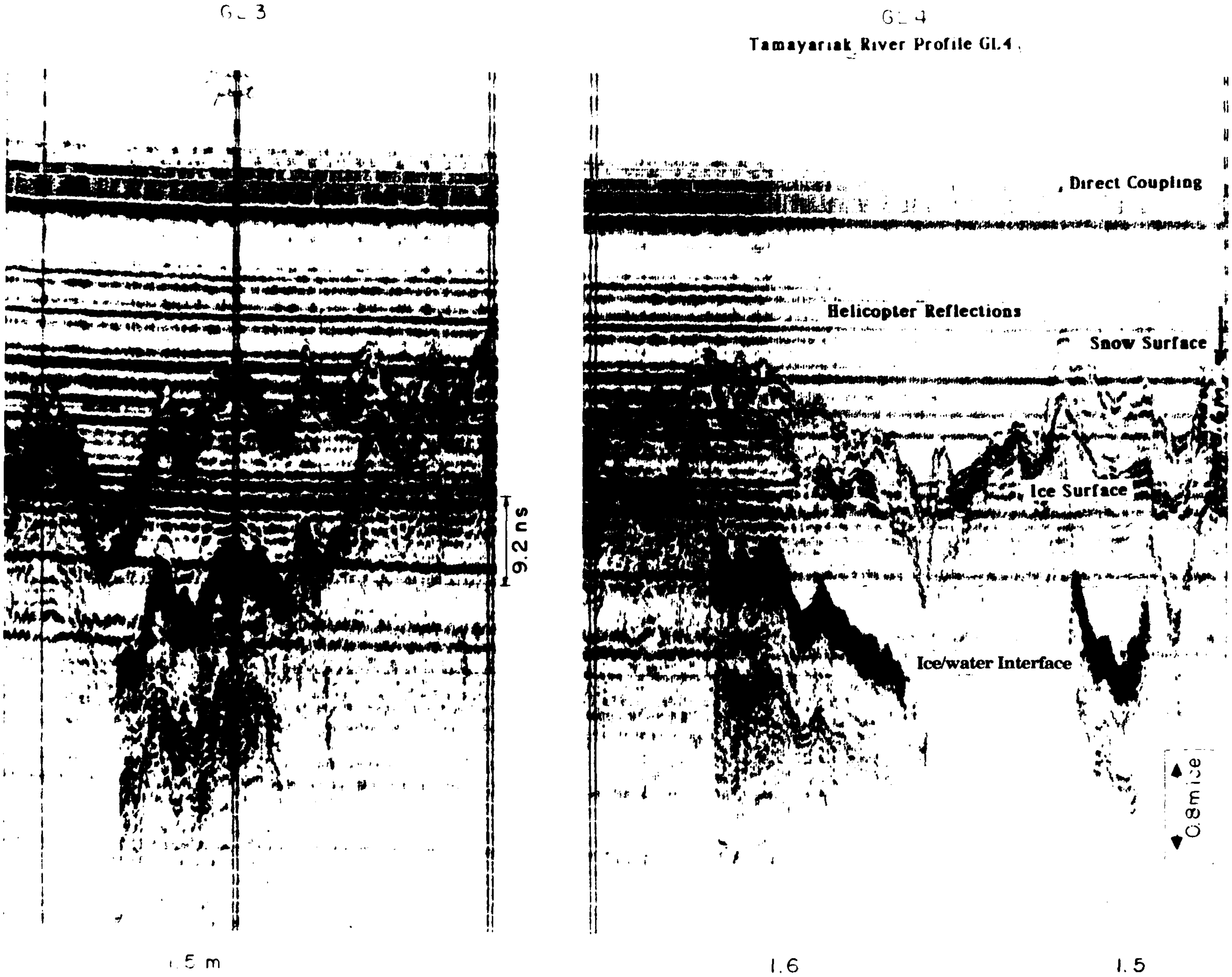

Figure 6. Radar returns over the Tamayariak River, profiles GL3, GL4.

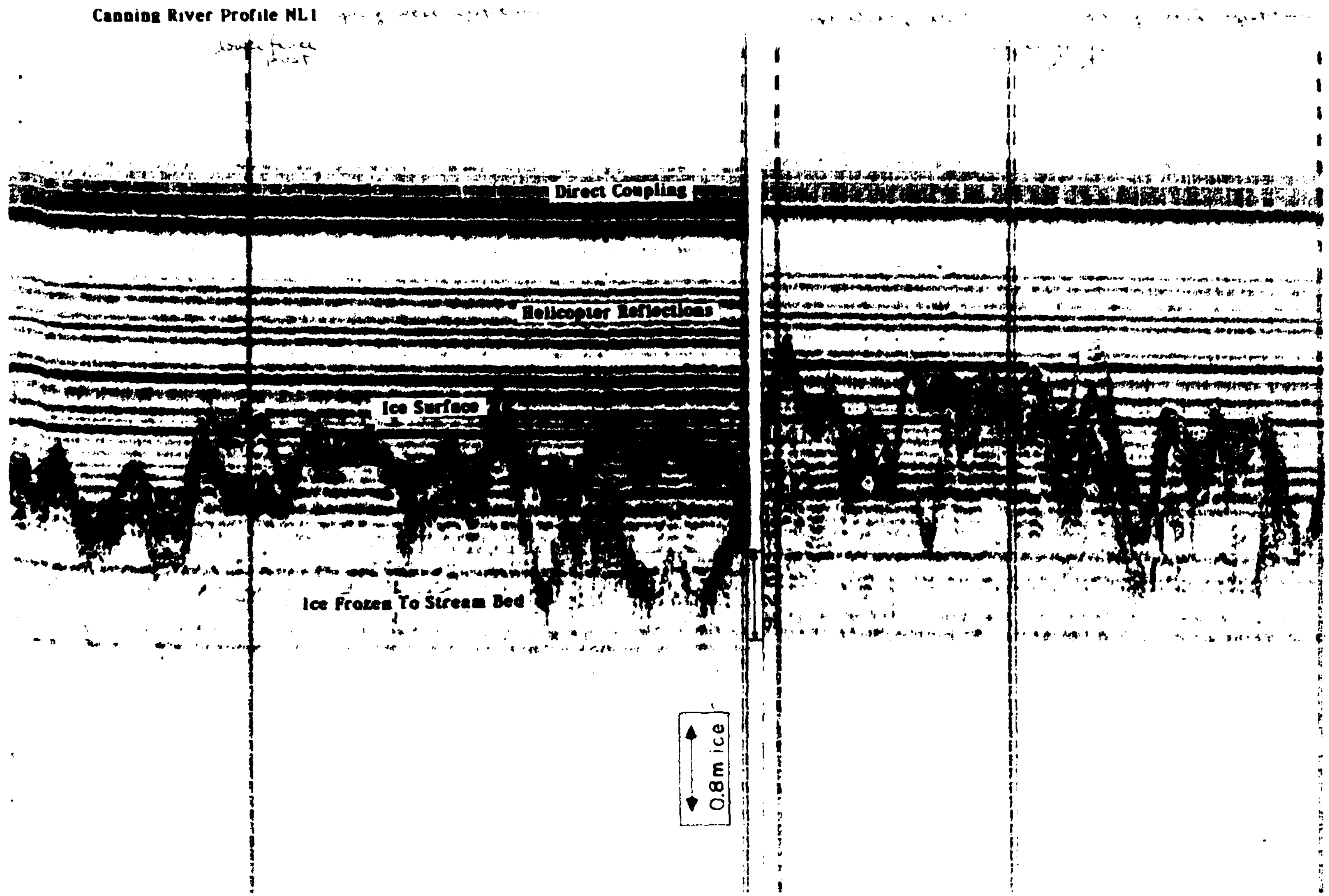

Figure 7. Radar returns over the Canning River, profiles NL1, NL2.

low, the ice is grounded to a frozen gravel bottom. Moderate intensity seen in some of the other data probably indicates ice grounded on an unfrozen bottom.

Figure 5 has an ice depth scale of 0.8 m per vertical division. This scale is to be used only to measure ice depth between the ice surface and bottom reflections. Close examination of the figure between some mounds reveals a very thin ice cover. There are a number of figures in the data set for which a scale of 1.46 m per vertical division applies, including the entire data set for Sadlerochit Springs and Kaktovik Lagoon, plus eleven transects on the Canning River (AX5, BX1, BX2, BX3, BX4, CL1, CX1, E1, E2, E3 and E4). This different scale is easily identified on the figures by the compressed width of the radar reflections. The vertical broken lines indicate features of interest such as an "ice mound" or a channel margin. Ice depths are given beneath some of these lines.

Figure 6 shows a short profile from a section recorded on the Tamayariak River where a thick snow section had accumulated on the outside bend of the river. Clear reflections from both the top of the snow and top of the ice surface can be seen along with bright radar returns from water beneath the ice. Figure 7 shows a profile from the Canning River profile where no water returns are visible and we suspect the ice is frozen to the river bed. A smooth and bare ice surface and placement of the ground returns within the constant amplification region of the radar scan window account for the ice surface reflection appearing darker than all later returns.

River ice mounds—field measurements

On several of the rivers, ice mounds were observed rising above the relatively smooth surface ice. These features were generally elongated, with concave surfaces leading to the top and a surface crack and/or gap along the top of the mound-shaped "icing." However, a few mounds were observed that were circular (Fig. 8), probably rising 1.2 to 2.4 m above the level ice sheet, with radial cracks and gaps extending to the top. The elongated mounds were generally oriented in the direction of the stream channels. The associated ice sheet in the mounds appeared to have crept from an initial horizontal position, with cracks forming along the top surface of the ice sheet. From a qualititative estimate, the large mounds (1.5–3 m in height) generally contained unfrozen water that was detected with the radar.

On the Sadlerochit River, one circular and two elongated mounds were examined in more detail to estimate the extent of the associated water quantities. Figure 9 is a plan view of the three mounds and Figures 10 and 11 give side and longitudinal views, respectively, of the larger mound that was 2.7 m above the surrounding level river ice surface, which itself was 1.2 m thick. Measurements of magnetic induction over the mounds, detailed radar profiles over and adjacent to the mounds and direct drilling of the ice were performed to measure the ice thickness, water depth and the surficial area of water zones.

The Sadlerochit radar transects A1–A4 (App. B) were run perpendicularly while transects B1–B4

Figure 8. Typical ice mound.

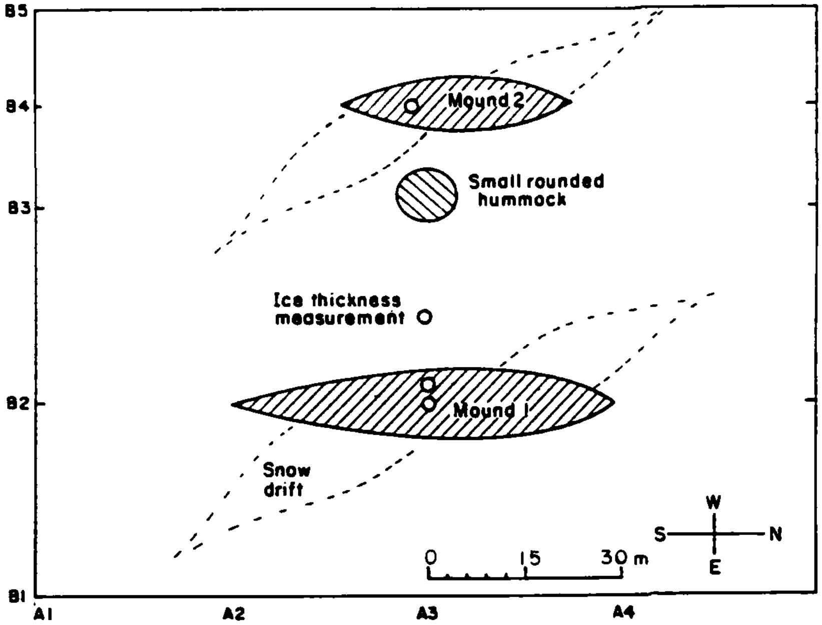

Figure 9. Plan view showing extent of surface area of the three mounds.

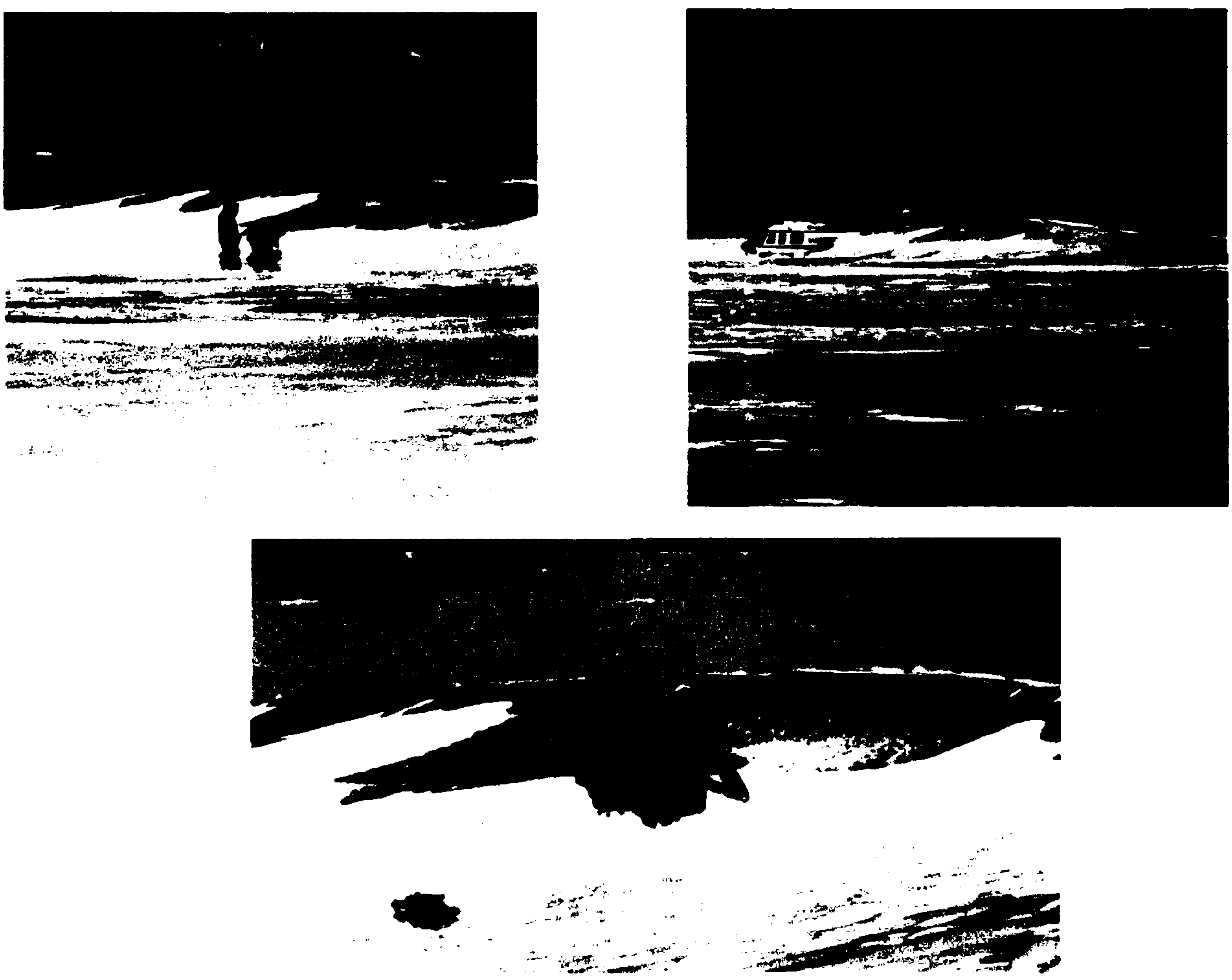

Figure 10. Side views of ice mound 1.

Figure 11. Longitudinal views down the long axis of mound 1.

were taken parallel to the mounds. Transects A1, A4, and B1 were run over the smooth ice sheet upstream, downstream, and on the east side, respectfully, of mound 1 to detect any water that could have been surrounding the study site. A radar transect on the west side of mound 2 was not performed. It can be seen in these transects that no water was detected entering or leaving the control area on three sides in a horizontal direction. The data indicate that the ice sheet was frozen to the river bed in all transects surrounding the mounds.

Transects A2 and A3 were flown perpendicularly to the mounds with A3 directly over the center of both. Transect A2, flown on the upstream end of the mounds, indicates water beneath only one mound, while A3 indicates water beneath both mounds.

Transects B2 and B4 were run parallel over the top of the mounds. The radar returns indicate water beneath a long portion of the mounds. The estimated lengths where water was present are roughly 30 and 53 m for mounds 1 and 2, respectively.

The magnetic induction survey using the EM-31 was also conducted perpendicular and parallel to the mounds. All readings were made with the antennas horizontal coplanar (HCP) with the unit one meter above the surface unless noted otherwise. A transect was run in an east/west direction over both mounds along the same line that radar transect A3 was flown. Starting the survey on the frozen gravel and traversing over smooth ice, we recorded readings of 0.0 mS/m for the ice and frozen ground and only when the unit was directly on top of mound 1 did a reading of 0.15 mS/m register.

The readings for mound 2 (when the unit was on the east-sloping face about 1 m from the top) were 1.0 mS/m HCP and 0.0 for the vertical coplanar direction (VCP). On top of the mound, readings of 0.85 and 0.0 mS/m for HCP and VCP respectively were recorded, while on the west-sloping face

readings of 0.2 and 0.2 mS/m were recorded for both HCP and VCP. An HCP profile taken along the top (ridge line) of mound 2 gave readings varying from 0.5 to 1.2 mS/m over a distance of 21 m, which indicated the presence of water. Cross-sectional readings at a second transect approximately 10 m north of the first one indicated the presence of water about 2.0 m from the top on each sloping face, for a total width of about 4.0 m.

Ice thickness measurements were conducted on both mounds. On the level ice surface next to mound 1, the thickness was 117 cm with the ice grounded to the bed, while 4.9 m from the top on the west-facing slope the thickness was 183 cm and the ice was grounded to the river bed as well. The ice condition at the top of mound 1 consisted of a 60-cm-wide crack in which we were able to stand to a depth of about 80 cm. A 3-cm-wide crack extended down about 60 cm more. The total ice thickness was 2.2 m, and the water depth between the bottom of the ice and the gravel bed was 1.2 m. During drilling the water rose about 30 cm above the top of the 3-cm crack and receded in about 2 minutes to no flow out the top as the pressure was relieved. Water also escaped from cracks in the upper 60 cm of the drilled hole and flowed toward both ends of the mound.

The ice thickness in the center of mound 2 was 2.1 m and, again, the water was under pressure as it rose several centimeters above the top of the ice and then stopped flowing after 5 minutes or so. The water depth was greater than 1.2 m below the bottom of the ice and the gravel bed was not reached. Surprisingly, the horizontal extent of the unfrozen water beneath mound 2 indicated by the radar return was greater than that beneath mound 1, even though mound 1 was roughly twice as long and slightly higher than mound 2.

The range in possible volumes of water above the gravel surface for mound 2 can be estimated based on the information from the radar surveys plus the one ground-truth water depth. The length of the unfrozen water zone from transect B4 is roughly 53 m. The range in widths is estimated at 5–10 m and a conservative depth is 1.2 m at the center. If a rectangular section along the entire length is assumed, then the total volume might be between 300 and 600 m^3. The shape of the water cavity over the entire length is probably more elliptic than rectangular, based on observations of frost mound cavities and the expectation that the water depth would decrease toward the elongated ends of the mound. If a pyramidal section is assumed (with a height of 1.2 m) and one side is 53 m long with a "horizontal base," the range in water volumes using widths of 5 and 10 m is 100–200 m^3.

BACKGROUND LITERATURE SEARCH

A computerized search of the CRREL Cold Regions Bibliography Data Base, using key words that could describe these river ice mounds, identified CRREL Draft Translation 399, *Siberian Naleds* (Alekseev 1973). This translation describes river ice mounds, similar to the features we observed on the rivers in the ANWR, which are referred to as "naled heaving hummocks" because of their formation in the river. Individual contributors to this compilation often refer to these river hummocks as mixed naleds, the term "mixed" deriving from the source of water associated with the hummock formation, but no one actually formulates or documents the process that describes the development. Based on English abstracts of untranslated Russian literature, there appears to be additional documentation on the occurrence of river ice mounds.

The natural processes that form these "mounds" appear to be freezing and expansion of ice that totally encapsulates a water body. Freezing from all sides generates sufficient pressure by compressing the water to cause an upward creeping motion of the ice sheet, cracking at the top and possibly subsequent flooding that relieves the pressure, and then refreezing of the crack followed by more creep due to continued confined inward ice growth. It was not possible to determine conclusively if deep sources of water from within the subchannel permafrost may also be flowing toward the surface. Such sources of water could cause additional pressure and supply water for the large extent of the hummocked ice cover.

CONCLUSIONS AND RECOMMENDATIONS

Unfrozen water was found in many sections of all rivers investigated in the Arctic NWR. In the braided channels it was found under ice mounds that occurred throughout the channel. The elongated shapes of the ice mounds were generally oriented along the direction of the stream channels. A realistic volume estimate for unfrozen water above the river bed for one 55-m-long and 3-m-high mound would be no more than about 100 m^3. The quantity of water in the unfrozen gravels be-

neath the mounds could not be estimated. It is concluded from the radar surveys that near-surface unfrozen water occurs only under about 70% of the mounds in these areas at this time.

Sources for the water are only speculative. Water probably cannot flow through cracks from sources beneath the permafrost because of the extensive depth and temperature of permafrost in the area, although we are unable to prove this. Flows through a thaw bulb or in isolated pockets beneath the river bed are regarded as the probable source and may have gone undetected by our instruments. The exact mechanism for generating the ice mounds is not entirely clear.

The radar unit is much more sensitive to the ice/water interface than is the magnetic induction technique because the former method senses contrasts in electrical properties at interfaces whereas the latter is sensitive to bulk properties of individual media. For example, the results of the EM-31 water detection survey indicated water beneath a 21-m transect along mound 2, whereas the radar gave a distance of 53.3 m.

The following recommendations are made with a view toward understanding the origin and dynamics of mound formation so as to predict water availability in the High Arctic.

1. Given the exact position of many of these features made possible by the GPS data, the mound locations should be examined in late summer to determine the presence of any springs, scour holes or other unusual hydraulic features.

2. A drilling program should be undertaken to assess water volume, rechargeability and water quality. This would best be done in April and May when weather is more accommodating and the ice is still present.

3. Synthetic aperture radar (SAR) imagery of the area should be examined for presence of mounds and their intensity of return as a possible indicator of water. The ice mound texture was very consistent and may be an excellent propagation medium for microwaves, despite the cracks.

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APPENDIX A. POSITIONS OF RIVER CROSS SECTIONS USING GPS

The positions of several cross sections for several rivers and two lakes using the GPS are given below. The stations listed were recorded when two or more satellites were visible to the GPS antenna and stable readings could be observed on the computer. Included in this Appendix are comments by George Elliot of the U.S. Fish and Wildlife Service who was the flight navigator and selected the transect locations. These comments are Mr. Elliot's personal ratings of the accuracy of the transect locations both by reference to USGS topographic maps and by the GPS system. The authors wish to state that the topographic maps were produced in 1955, since when features may have changed, and that the maps themselves state "not to be used for navigational purposes."

Table A1. GPS locations of several river and lake transects.

Location	*Line*		*Latitude*	*Longitude (W. of Greenwich)*
Bar Main Hangar			70 08 11	143 35 24
Refuel position	28-Mar-88		69 57 29	145 40 51
Lakes				
	L3	start	69 59 07	143 39 45
		fin	69 59 18	143 42 40
	L4	start	69 55 53	143 37 51
		fin	69 55 49	143 39 03
Okpilak River	BX1	start	69 51 57	143 45 58
		fin	69 51 52	143 46 42
	CX1	start	69 53 42	143 48 06
		fin	69 53 41	143 49 14
Tamayariak River	CX1	start	69 56 08	145 40 51
		fin	69 56 06	145 41 44
	CX2	start	69 56 ??	145 41 34
		fin	69 56 21	145 42 21
	CX3	start	69 55 28	145 35 31
		fin	— — —	— — —
Canning River	DX1	start	69 52 14	146 19 50
		fin	69 52 11	146 20 36
	LL1	start	70 03 53	145 51 45
		fin	70 04 04	145 50 29
	ED1	start	70 02 28	145 50 45
		fin	70 04 03	145 53 27
	ED2	start	70 01 09	145 50 33
		fin	70 00 56	145 51 08
	ED3	start	70 00 06	145 54 00
		fin	69 59 55	145 54 57
	J1	start	70 03 00	145 58 30
		fin	70 02 04	145 57 36
	J2	start	70 01 55	145 56 20
		fin	70 02 05	145 55 26

Table A1 (cont'd). GPS locations of several river and lake transects.

Location	*Line*	*Latitude*				*Longitude (W. of Greenwich)*		
	K1	start	70	03	49	145	51	27
		fin	70	04	00	145	50	35
	NX1	start	70	04	57	145	43	09
		fin	70	05	30	145	38	46
Hulahula River	LL1	start	70	02	00	144	00	21
		fin	70	02	03	144	01	37
	LL2	start	70	01	31	144	01	50
		fin	70	01	26	144	01	29
	LL3	start	70	01	18	144	01	02
		fin	70	00	39	144	01	44
	LL4	start	70	00	28	144	01	26
		fin	69	59	59	144	02	06
	KL1	start	69	57	50	144	02	37
		fin	69	57	41	144	02	58
	KL2	start	69	57	23	144	03	00
		fin	69	56	45	144	03	34
	KL3	start	69	54	20	144	03	29
		fin	69	53	54	144	04	28
	KL4	start	69	51	04	144	07	37
		fin	69	51	01	144	07	47
	KL5	start	69	49	36	144	07	37
		fin	69	49	16	144	07	47
Jago River	BL1	start	69	44	39	143	35	21
		fin	69	44	36	143	35	34
Sadlerochit River	AX1	start	69	39	30	144	22	59
		fin	69	39	30	144	22	59
	AX2	start	69	38	55.4	144	20	59.9
		fin	69	39	22.7	144	22	43
	AX3	start	69	39	22.6	144	22	43
		fin	69	39	21.4	144	22	46.8
	BX1	start	69	41	51.4	144	23	29.3
		fin	69	41	49.8	144	24	06
	BX2	start	69	41	50.6	144	23	54.1
		fin	69	40	57	144	24	14.1
	BX3	start	69	40	57.1	144	24	22.4
		fin	69	40	53.9	144	24	18.6
	CX1	start	69	42	59.5	144	19	05
		fin	69	43	38	144	16	08
	CX2	start	69	42	49	144	22	01
		fin	69	42	37.3	144	23	18.2
	CX3	start	69	42	36	144	23	14
		fin	69	42	39.6	144	23	33.6

Table A1 (cont'd).

Location	*Line*		*Latitude*			*Longitude (W. of Greenwich)*		
	DX1	start	69	43	37	144	21	(12–26)
		fin	69	43	24	144	19	(22–28)
	DX2	start	69	44	13	144	22	(40–60)
		fin	69	44	(52–58)	144	24	(30–43)
	DX3	start	69	44	12.6	144	20	50.1
		fin	69	44	35.9	144	22	03.9
	DX4	start	69	44	48–49	144	21	(55–58)
		fin	69	45	11.3	144	21	13
	DX5	start	69	44	44	144	22	04
		fin	69	45	14	144	25	(10–16)
	DX6	start	69	45	35	144	27	(24–31)
		fin	69	46	06	144	30	(37–47)
	DL1	start	69	44	05	144	20	44
		fin	69	44	50	144	20	32
	EL1	start	69	45	55	144	17	55
		fin	69	46	53	144	19	07
	FL1	start	69	50	11	144	19	49
		fin	69	50	34	144	23	02
	GL1	start	69	53	21	144	21	16
		fin	69	54	32	144	19	48
Sadlerochit Springs Icing	A	start	70	00	56.2	145	15	44
		fin	70	00	54	145	18	58
	B	start	70	01	10	145	21	12.7
		fin	70	01	(21.6–23)	145	22	(37–44)
	C	start	70	01	(30–31)	145	23	(43–48)
		fin	70	01	46	145	25	(41–50)
	D	start	70	01	58	145	27	12
		fin	70	02	20	145	29	56
	E	start	70	02	29	145	31	09
		fin	69	45	05.2	144	27	28

Table A2. USFWS ratings of accuracy of transect placement.

Location of reference point or flight line	*Rating of transect placement on maps based on visual landmarks*	*Rating of GPS transect placement compared to map features*
Bar Main Hangar	Very good	Very good
Refuel location	Good	Very poor—7 mi. off
Lakes		
L3	Good	Good—within 0.25 mi., direction correct but start may be off
L4	Good	Very good
Okpilak River		
BX1	Good	Good
CX1	Poor	May be good?
Tamayariak River		
CX1	Good	Fair—within 0.5 mi.
CX2	Good	Fair—within 0.5 mi.
CX3 (start)	Good	Poor—2.5 mi. off.
Canning River		
DX1	Good	Poor—1.5 mi. off.
LL1	Poor	May be good?
ED1	Good	Poor—start 1.25 mi. off, fin 3 mi. off, direction 90 deg. off
ED2	Good	Fair—within 1 mi., direction correct
ED3	Fair	Fair—within 1 mi., direction correct
J1	Poor	May be fair?—direction and start in question
J2	Poor	May be good?
K1	Poor	May be good?
NX1	Very good	Poor—2 mi. off, direction 45 deg. off, too long
Hulahula River		
LL1	Good	Poor—direction off, shows cross section not longitudinal section
LL2	Fair	Fair—direction off
LL3	Marginal	May be good?
LL4	Marginal	May be good?
KL1	Poor	May be good:—too short?
KL2	Poor	May be good?
KL3	Poor	May be good?
KL4	Poor	May be good?
KL5	Poor	May be good?
Jago River		
BL1	Good	Poor—Start good but finish too short and in wrong direction
Sadlerochit River		
AX1 (Start)	Very good	Good—within 0.125 mi.
AX2	Very good start Fair finish	Poor—1 mi. off
AX3	Fair	Poor—1 mi. off
Sadlerochit River		
BX1	Poor	May be good?
BX2	Poor	May be good?
BX3	Poor	May be good?
CX1	Poor	May be good?
CX2	Poor	May be good?
CX3	Poor	May be good?
DL1	Poor	May be good?—displaced 0.25 mi. to east of river channels on map
The following DX transects are rated assuming DL1 GPS positions are accurate		
DX1	Poor	Fair/poor—0.5 mi. off, too long
DX2	Poor	Poor—start 0.5 mi. off but wrong direction and too long

Table A2 (cont'd).

Location of reference point or flight line	*Rating of transect placement on maps based on visual landmarks*	*Rating of GPS transect placement compared to map features*
DX3	Poor	May be good?—direction may be off 45 deg
DX4	Poor	Poor—start may be good but direction off 90 deg
DX5	Poor	Poor—wrong direction, too long, fin 2 mi. off
DX6	Poor	Very poor—start 2.5 mi. off, fin 4 mi. off, wrong direction
EL1	Poor	Poor—fin may be good but start 1 mi. from main river channels on map
FL1	Poor	Poor—start may be good but fin 1.5 mi. off, direction 90 deg. off
GL1	Start good Fin fair	Good
Sadlerochit Springs Icing		
A	Fair	Very poor—30 mi. off
B	Fair	Very poor—30 mi. off
C	Fair	Very poor—30 mi. off
D	Fair	Very poor—30 mi. off
E	Fair	Very poor start—30 mi. off, fin good

APPENDIX B: DETAILED RADAR TRANSECTS OF ICE MOUNDS ON THE SADLEROCHIT RIVER

These radar returns represent detailed transects over the three ice mounds on the lower end of the Sadlerochit River near the "lower USGS fence post marker." Transects A1–A4 were flown east to west beginning upstream of the mounds, then over them, and then finishing downstream of them. Transects B1–B4 were flown south to north, parallel to the river, and adjacent and over the ice mounds.

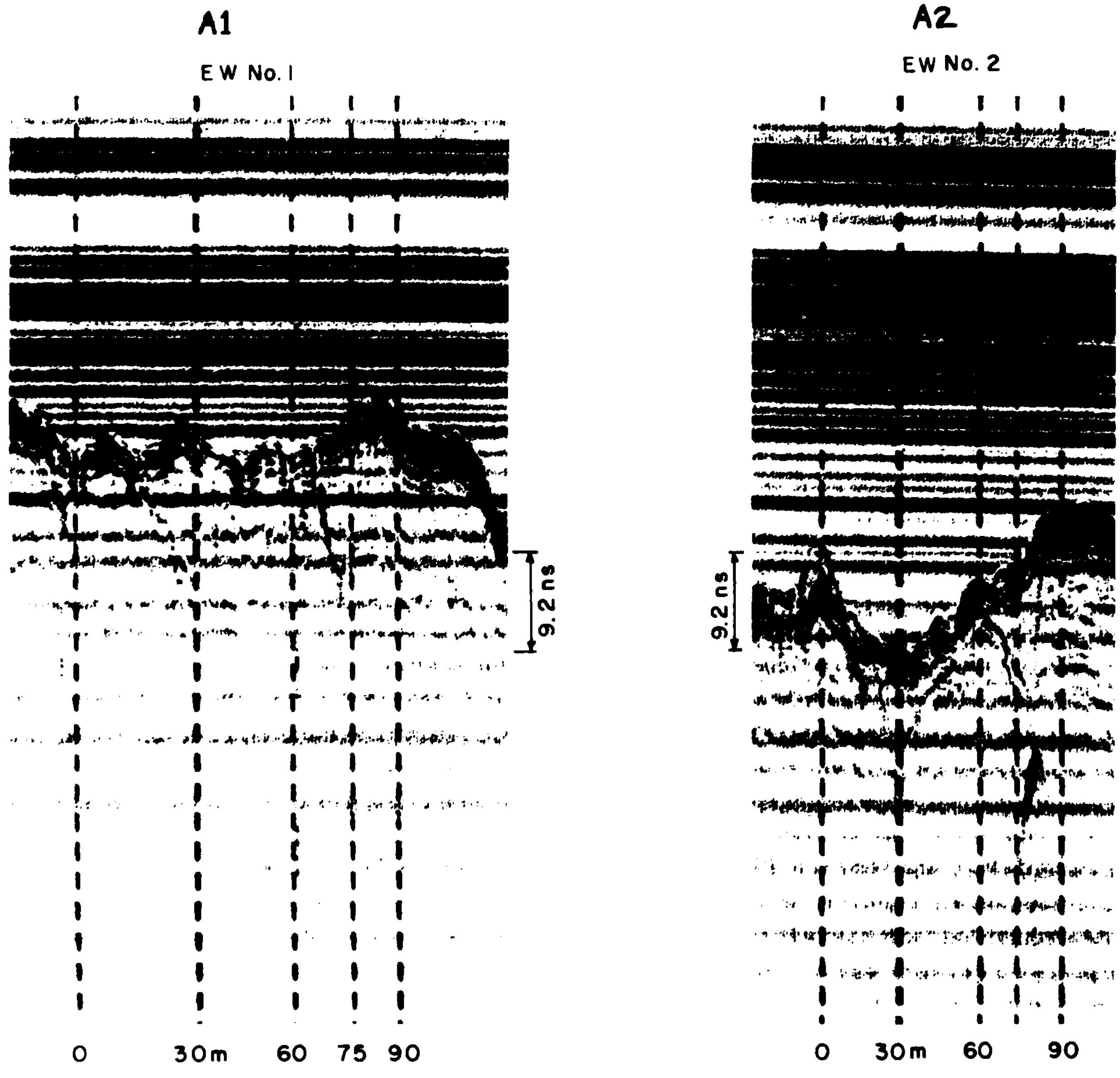

Figure B1. Sadlerochit River, A1, A2.

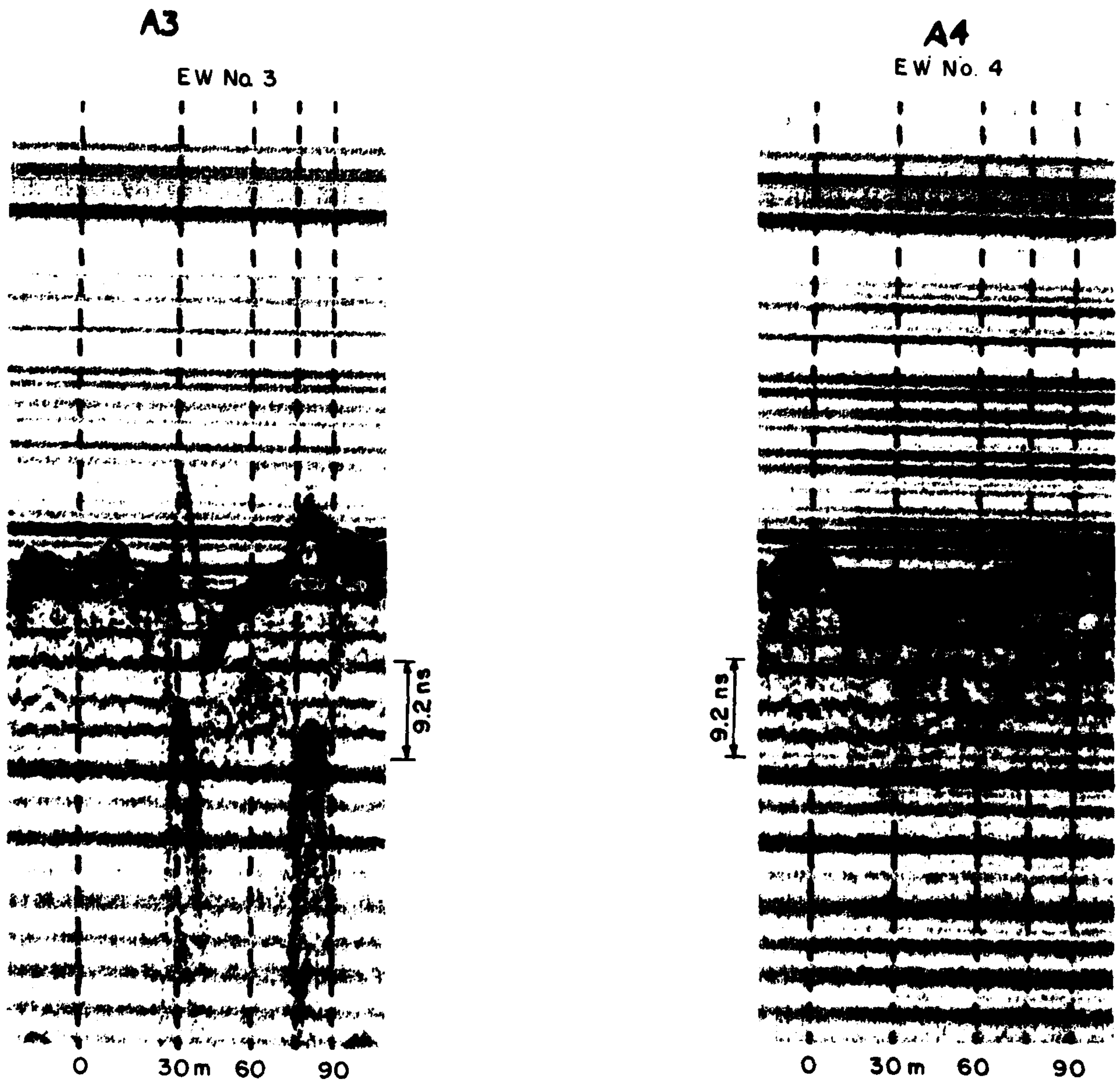

Figure B2. Sadlerochit River, A3, A4.

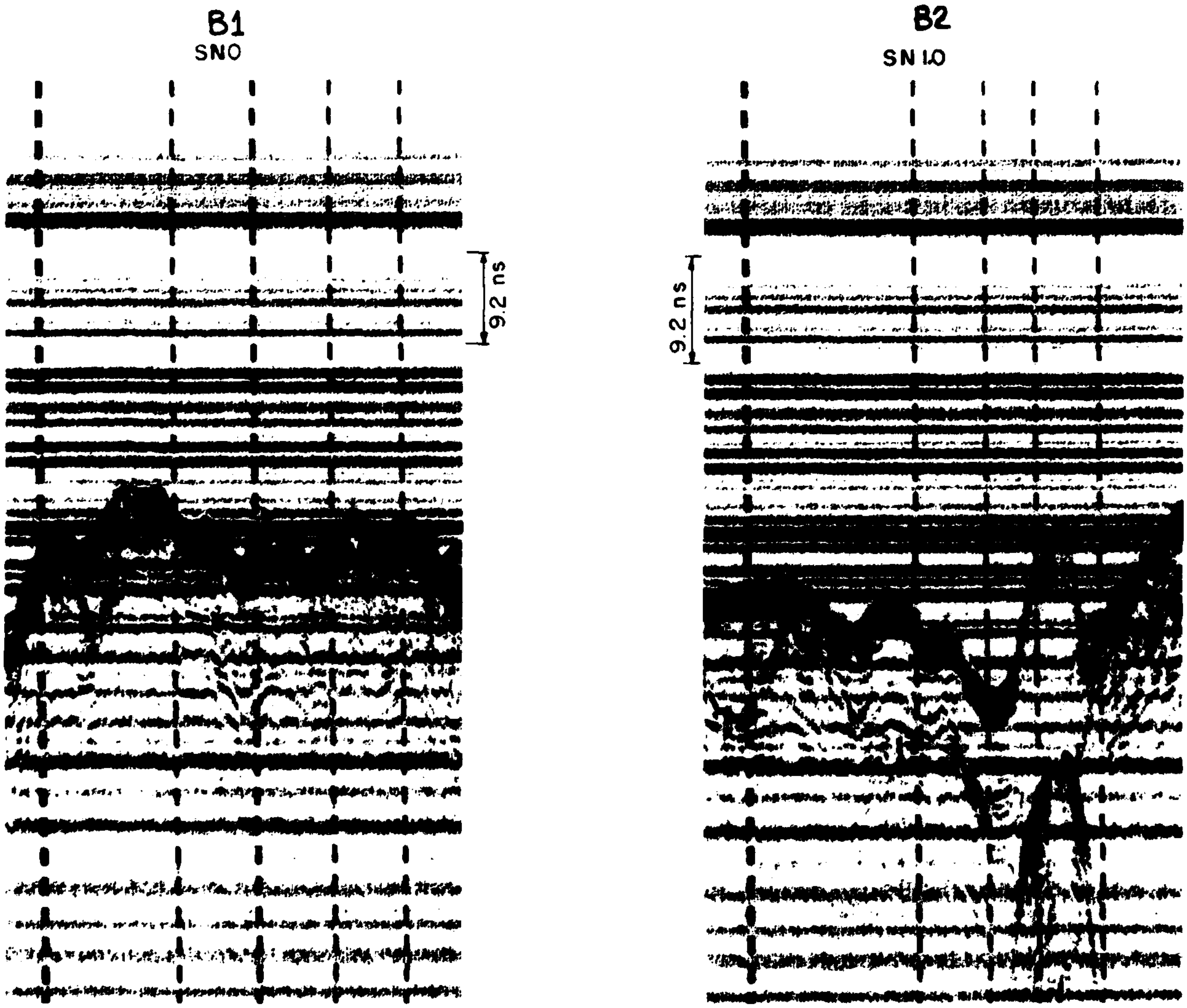

Figure B3. Sadlerochit River, B1, B2.

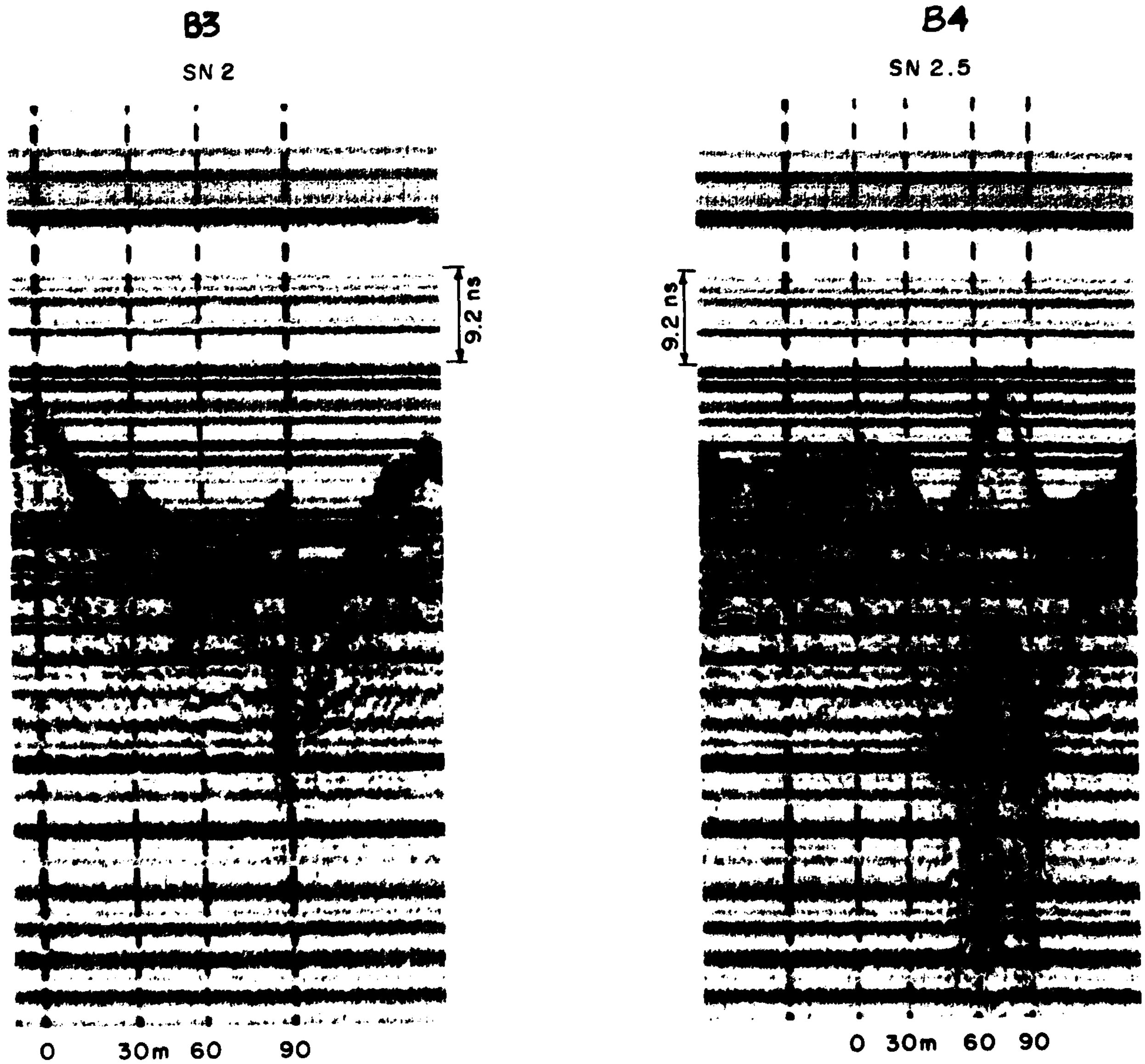

Figure B4. Sadlerochit River, B3, B4.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Arcone, Steven A.

Water detection in the coastal plains of the Arctic National Wildlife Refuge using helicopter-borne short pulse radar / by Steven A. Arcone, Allan J. Delaney and Darryl J. Calkins. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1989.

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